FINE SCALE VARIABILITY IN SOIL FROST DYNAMICS SURROUNDING CUSHIONS OF THE DOMINANT VASCULAR PLANT SPECIES (*AZORELLA SELAGO*) ON SUB-ANTARCTIC MARION ISLAND

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ABSTRACT. Through changing soil thermal regimes, soil moisture and affecting weathering and erosion processes plants can have an important effect on the physical properties and structure of soils. Such physical soil changes can in turn lead to biological facilitation, such as vegetation-banked terrace formation or differential seedling establishment. We studied the fine scale variability in soil temperature and moisture parameters, specifically focusing on frost cycle characteristics around cushions of the dominant, vascular plant species, *Azorella selago*, on sub-Antarctic Marion Island. The frost season was characterised by numerous low intensity and very shallow frost cycles. Soils on eastern cushion sides were found to have lower mean and maximum temperatures in winter than soils on western cushion sides. In addition, lower variability in temperature was found on eastern cushion sides in winter than on western cushion sides, probably as a result of higher wind speeds on western cushion sides and/or eastern, lee-side snow accumulation. Despite the mild frost climate, extensive frost heave occurred in the study area, indicating that needle ice forms at temperatures above –2°C. Our results demonstrate the effectiveness of frost pull as a heave mechanism under shallow frost conditions. The results highlight the importance of *Azorella* cushions in modifying site microclimates and of understanding the consequences of these modifications, such as potentially providing microhabitats. Such potential microhabitats are particularly important in light of current climate change trends on the island, as continued warming and drying will undoubtedly increase the need for thermal and moisture refugia.

Key words: frost heave; Sub-Antacrtic, cushion plant, microclimate

Introduction

The effects that plants have on the biotic and/or abiotic properties of soils have been well-studied, especially in the context of plant-soil feedbacks (see Kulmatiski *et al.* 2008 for a recent review). Specific attention has been paid to the effects plants have on microbial communities (Kardol *et al.* 2007), soil pathogens (Mills and Bever 1998) and soil chemical properties (Bezemer *et al.* 2006). However, through changing soil thermal regimes (Ng and Miller 1977; Pérez 1987a; Arroyo *et al.* 2003), soil moisture status (Badano *et al.* 2006; Cavieres *et al.* 2007) and affecting weathering and erosion processes (see Gabet *et al.* 2003 for a recent review), plants have an equally important effect on the physical properties and structure of soils. Such changes in soil physical properties could in turn facilitate the establishment or survival of other plant (Arroyo *et al.* 2003; Cavieres *et al.* 2007) and animal species (Hugo *et al.* 2004). As such these physical pathways often provide excellent examples, not only of plant-soil feedbacks (Kulmatiski *et al.* 2008), but of ecosystem engineering (Jones *et al.* 1994) in general.

Interactions between the vegetation and physical soil properties are particularly relevant in climatically extreme environments, such as the islands of the sub-Antarctic (Ng and Miller 1977; Frenot *et al.* 1998). These areas are often subjected to adverse weather conditions, leading to recurrent soil frost cycles and soil instability, which both affect (Tierney *et al.* 2001; Pérez 2002), and are affected by vegetation (Ng and Miller 1977; Matthews *et al.* 1998). On sub-Antarctic Marion Island the dominant vascular cushion plant, *Azorella selago*, is said to play an important role in landscape evolution by interacting with frost creep and other sediment movement processes (Holness and Boelhouwers 1998; Boelhouwers *et al*. 2003; Haussmann *et al*. 2009). As prevailing warming and drying on the island is likely to affect their nature and extent, understanding these biogeomorphic interactions is especially important for predicting the consequences of climate change for landscape evolution. Vegetation-banked terraces for example have been seen as synergistic, self-regulating systems, where cushion growth facilitates terrace formation and terraces in turn provide favourable conditions for further latitudinal cushion growth (Haussmann *et al*. 2009). However, relatively little is known about the mechanisms (such as through temperature and moisture amelioration) by which terrace formation and related cushion establishment provide favourable conditions for cushion growth.

A number of studies have focussed on the relationship between vegetation cover and soil frost cycles (Ng and Miller 1977; Walker *et al*. 2003). These studies often relate frost cycle dynamics to canopy cover, organic horizon thickness or plant biomass. However, cushion plants have a compact, prostrate growth-form and as such do not provide a canopy or litter cover to the surrounding soil. Nevertheless, the role of cushion plants in modifying frost cycle dynamics (see for example Pérez 1987a) should not be overlooked. On Marion Island for example, temperature and moisture levels inside *Azorella* cushions have been shown to differ markedly from surrounding ground temperatures (Huntley 1971; Nyakatya and McGeoch 2008). Furthermore, by colonising exposed slopes (Huntley 1972) and because of their extensive root system (Frenot *et al*. 1998), *Azorella* cushions are likely to stabilise slopes and play an important role in biogeomorphic succession, i.e. succession facilitated by plant-landform interactions (Corenblit *et al*. 2008). In large areas of Marion Island these cushions are the dominant form of vegetation cover and very often one of only a few vascular plant species, particularly at high altitudes (Huntley 1971) and as such play a dominant role in maintaining ecosystem structure and function on the island.

Although temperature and moisture levels have been measured inside *Azorella* cushions and compared to those next to the cushion (Huntley 1971; Nyakatya and McGeoch 2008), no detailed fine-scale measurements of soil thermal conditions and frost heave around cushions have previously been done. As these are the sites where seedlings are likely to establish and cushion growth is likely to commence (as opposed to inside the plant), determining the spatial variability of frost dynamics around cushions is also important. Furthermore, as frost cycle characteristics such as frost durations, frequency of cycles and amplitudes of temperature variations have been shown to affect soil nutrient budgets and micro-organisms (see Henry 2007 for a recent review), variability in frost cycle dynamics is certainly biologically very relevant.

Here we hypothesize that soil thermal and moisture patterns show spatial variation around *Azorella* cushions that will affect soil frost frequency, intensity and duration on different aspects of the cushion. This may take the form of shading affecting the micro-scale radiation balance (Oke 1987, p. 232), leeside snow accumulation (snow fence effect) providing thermal insulation and altering ground frost regimes (Hinkel and Hurd 2006) or windward sides of cushions showing drying and cooling effects due to enhanced evaporation.

Spatial variation in thermal and moisture regimes are subsequently expected to translate into differential frost heave and erosion around cushions. For example, cushion decay has previously been ascribed to leeside needle ice formation and heave-related turf exfoliation, resulting in crescent cushions advancing into the wind (Boelhouwers *et al*. 2003). We therefore further hypothesize that frost heave will be more effective on leeward cushion sides than on windward cushion sides.

Study area and site selection

Marion Island (46°54'S, 37°45'E), which forms part of the Prince Edward Island Group, is located in the southern Indian Ocean. The soil frost regime on the island is characterised by diurnal frost cycles and frequent needle ice formation (Boelhouwers *et al*. 2003) as a result of the island's maritime climate with both low annual (3.6°C) and diurnal (1.9°C) temperature ranges (Smith 2002) and high rainfall of just over 2000 mm per year (Le Roux and McGeoch 2008). Fellfield vegetation, consisting of open plant communities, is restricted to rocky, windswept ridges at lower altitudes, but is the dominant vegetation type above 200 m a.s.l. (Huntley 1971).

The specific site for this study was the Tafelberg area, an area situated on the eastern side of the island at approximately 300 m a.s.l. The vegetation at this site is classified as fellfield (Gremmen 1981)

Fig. 1. The three monitored cushions (a) the round-flat (RF) cushion, (b) the crescent-flat (CF) cushion and (c) the round-slope (RS) cushion. Arrows in the bottom left-hand corner point north

and is dominated by cushions of *Azorella selago*. Surface material consists of a matrix-supported, unsorted glacial till that is subject to superficial frost heave and creep. A 4–7 cm depth of sorting has been found at similar altitudes on grey lava (as opposed to younger black lava) on the island (Holness and Boelhouwers 1998). Boelhouwers *et al*. (2003) found a freeze-thaw frequency of 72 cycles per year at 200 m a.s.l. and 1 cm depth on the island, while Smith and French (1988) estimated the number of frost free days at 5 cm depth in fellfield below 300 m a.s.l. to be 273. Frost creep is considered the dominant form of sediment movement in this terrain (Holness 2001a).

Methods

Field procedure

Sample size was restricted by cost and time constraints to three *Azorella selago* cushions (Fig. 1), which were selected from the Tafelberg area. Although this sample size is small, we aimed at representing general cushion conditions on Tafelberg by choosing cushions of two commonly occurring shapes (round and crescent-shaped) and from two slope angles (flat and moderately sloping). Two cushions, one round and the other considered crescent-shaped, were selected from a relatively flat terrain (–5° slope angle with northerly aspect). These are hereafter referred to as RF (Fig. 1a) and CF (Fig. 1b) respectively. The CF cushion showed signs of decay on the southern cushion side and was therefore seemingly advancing in a northerly direction. The third cushion also had a round shape and was selected from a moderately sloping terrain (7–12° slope angle) with south-east orientation, i.e. the upslope cushion side faced north-west and the downslope cushion side south-east. This cushion is referred to as RS (Fig. 1c). Apart from aforementioned shape and slope criteria, cushion selection was based on cushion size (maximum cushion diameter of at least 50 cm) and nearest neighbour criteria (no neighbouring cushion within 1 m distance from study cushion).

Data loggers (Model MCS 130M1, MC Systems, South Africa) with soil temperature (Model MCS154, MC Systems, South Africa) and moisture probes (Decagon, Model EC-20, Decagon Devices) were used for soil temperature and moisture monitoring on eastern and western cushion sides, deemed the windward and leeward sides of cushions for this site. **Automated weather station (AWS)** measurements taken at hourly intervals from April 2007 to April 2008, as well as the presence of scattered heaved-out dowels on eastern cushion sides in April 2008 supported this initial hypothesis of a dominant westerly wind direction. Soil temperature and moisture probes were set to record instantaneous values every hour. The accuracy of the soil temperature probes is reported to be 0.2°C and that of the moisture probes 4% (volume/volume). The temperature probes were inserted at 50 mm distance from the cushion and 20, 50 and 100 mm depth and soil moisture probes at 50 mm distance and 50 mm depth. As a result of cost constraints, temperature and moisture measurements were performed at only one distance from the cushion. Less expensive i-button temperature loggers (DS 1922L/T Thermochron i-buttons, Dallas Semiconductor Corporation, USA) were initially used to measure temperatures at other distances and directions from the cushion. However, as differences between distances and directions were mostly smaller than the accuracy of the i-buttons (0.5°C), these data were not analysed.

All three microstations became inoperative early in November 2007. Therefore only 6 months of data were available from the measurements. However, a full year soil temperature record from the i-button temperature loggers around the cushions showed that the period from the beginning of May 2007 to the beginning of October 2007 contained more than 90 % of the frost cycles. Thus, data analysis, based on the May-October record, captured the main frost season. As a result of the microstation malfunctioning, soil moisture data were also only available for the first 6 months and only for the CF cushion (both sides) and the RF western cushion side.

Wooden dowels of 10 mm diameter and 100 mm length were used to measure frost heave around the cushions. The dowels were inserted completely (or as far as possible) into the soil in April 2007 (see Pérez 1987a; Holness 2004 for more on this method). The difference in exposed length between April 2007 and April 2008 was used as an indication of total annual frost heave. Soil erosion was measured using steel pins of 4 mm diameter and 300 mm length. The steel pins were inserted into the soil up to a depth of at least 200 mm, i.e. well below the depth of expected frost creep of 5 cm (Holness 2004). The difference in exposed pin length between April 2007 and April 2008 was used as an indication of erosion. Dowels and pins were alternated in a grid extending approximately 0.5 m from the cushion edge. The distance in between the grid nodes was between approximately 100 and 200 mm, depending on the presence of rocks. Dowels and erosion pins were measured in the field to 0.1 mm accuracy using a calliper.

Data processing and statistical analyses

All data were analyzed using the three cushions as replicates. Cushions were deemed suitable replicates despite differing in shape and slope angle, as no opposing trends were expected between cushions. Indeed, a visual comparison of temperature parameters for the three cushions separately confirmed that trends were not opposing.

Temperature and moisture data. Two sets of temperature parameters were calculated, namely frost indices and actual temperature parameters. As frost indices, numbers of frost cycles, durations of the frost events and their intensities were calculated. A frost cycle was identified as a drop in temperature below 0°C followed by a rise above 0°C. The duration of a frost event was defined as the length of time spent below 0°C and the intensity of the event as the absolute minimum temperature reached during the cycle. Mean frost event duration and intensity were calculated per month. In addition, total frost duration (the total length of time that the soil was frozen) was calculated per month. Actual temperature parameters consisted of means, maxima, minima and standard deviations as a measure of variability and were calculated per month. The same parameters were calculated for soil moisture.

All depths were used to compare the numbers of frost cycles between eastern and western cushion sides statistically, as, in this context, zero (indicating no frost cycles) is a sensible value. However, only the 2 cm depth data were used for comparison of durations and intensities, as the other two depths did not have substantial numbers of frost cycles. In this case a value of zero would be non-sensical, as it would incorrectly imply frost cycles with durations and intensities of zero.

Numbers of frost cycles were compared between cushion sides (east/west) using **Generalised Estimating Equations (GEE)**. A GEE provides a model for analyzing observations that are not temporally independent. In addition, it is capable of analyzing non-normally distributed variables (Liang and Zeger 1986). Direction (east/west) was used as the main independent variable of interest. The effects of depth and month were also tested, but interactive effects could not be tested using GEE. We used a negative binomial distribution for modeling the distribution of the independent variable.

Repeated measures analysis of variance (ANOVA) was used to test for differences in frost durations and intensities between cushion sides using direction (east/west) as independent variable. Only the 2 cm depth data were used, as the other two depths did not have a substantial number of frost cycles. Month was included as a co-variable and interactive effects between month and direction were also tested. Repeated measures ANOVA was also used to test for differences in mean temperatures, maxima, minima and standard deviations, using direction (east/west) as independent variable. Depth and month were included as co-variables and interactions between co-variables were also tested. Data were approximately normally distributed.

Soil moisture data were not analyzed as differences between cushion sides were smaller than instrument accuracy.

Heave and erosion data. Field photographs were used to measure the shortest distance from each dowel/ pin to the outer edge of the cushion and the compass direction from the centre of the cushion. Heave and erosion were compared between cushion sides (north-south and east-west) using non-

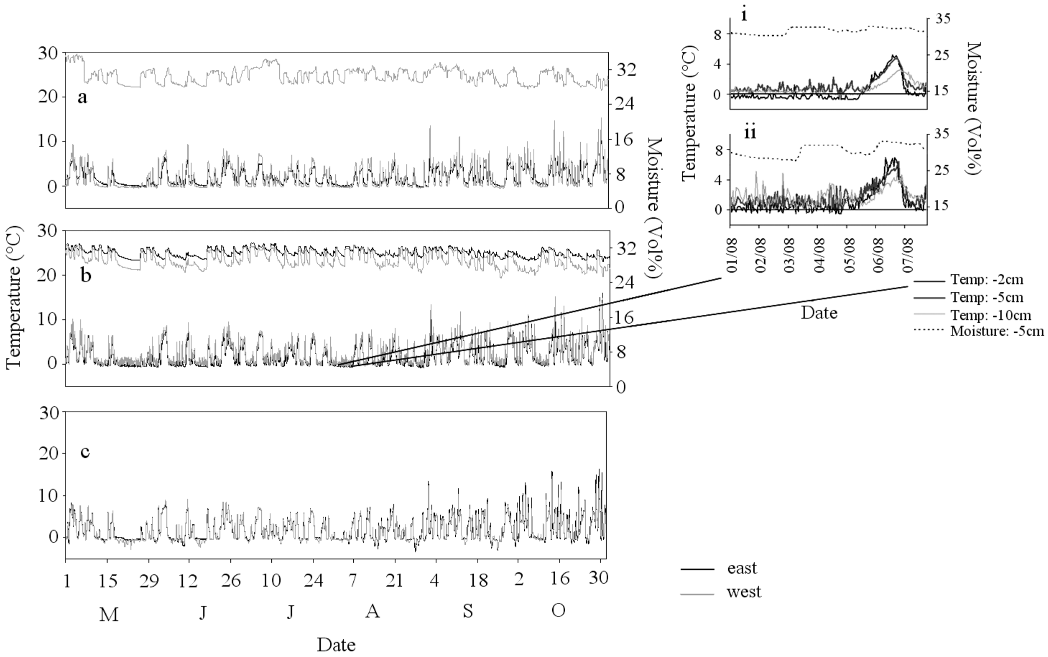

Fig. 2. Temperature and moisture time series for the six month measuring period at –2 cm for (a) the round-flat (RF) cushion, (b) the crescent-flat (CF) cushion and (c) the round-slope (RS) cushion. Notice the large number of fluctuations around 0°C characteristic of the frost season. Also notice the high, near-saturated soil moisture values throughout the series. The inlay shows a one week period for the CF cushion on (i) eastern and (ii) western cushion sides. Notice the sustained period of temperatures at or below 0°C up to the warm front passage on 5 August on the eastern cushion side, indicative of snow accumulation. Larger fluctuations on the western cushion side show that no snow has accumulated here

parametric (Kruskal Wallis analysis of variance (ANOVA)) tests. To determine the relationship between heave and erosion and distance from cushion Spearman rank correlation coefficients were calculated.

Results

Temperature data

Frost index analyses. The frost season was typically characterized by low intensity, shallow frost cycles, with many frost cycles being the result of fine-scale fluctuations around 0°C (Fig. 2). Over all three depths, eastern cushion sides were found to have significantly fewer frost cycles than western cushion sides ($Z = -2.06$, $p = 0.04$). The inlay in Figure 2 clearly shows the large number of fluctuations around 0 °C on a smaller time scale of one week for the CF cushion, as well as the soil moisture trends on eastern and western cushion sides.

Frost cycles lasted between 1 hour and more than 100 hours (Fig. 3a), although for all three cushions the majority of frost cycles had durations of less than 20 hours. No interactive effects were found between month and direction (east/west) for mean frost durations or total frost durations. Direction and month separately had no significant effect on mean frost durations. Only month had a significant effect on total frost durations, with August having the longest total frost duration and September and October having significantly shorter total frost durations than any of the other months.

Frost cycles in general were not very intense, with mean frost intensities above –1°C (Fig. 3b). No interactive effects were found for month and direction for average frost intensity. Furthermore average frost intensities did not differ significantly between months or directions.

Means, maxima, minima and standard deviations. No significant third order interaction was found between direction (east/west), month (May-October) and depth (2, 5 or 10 cm) for mean temperatures,

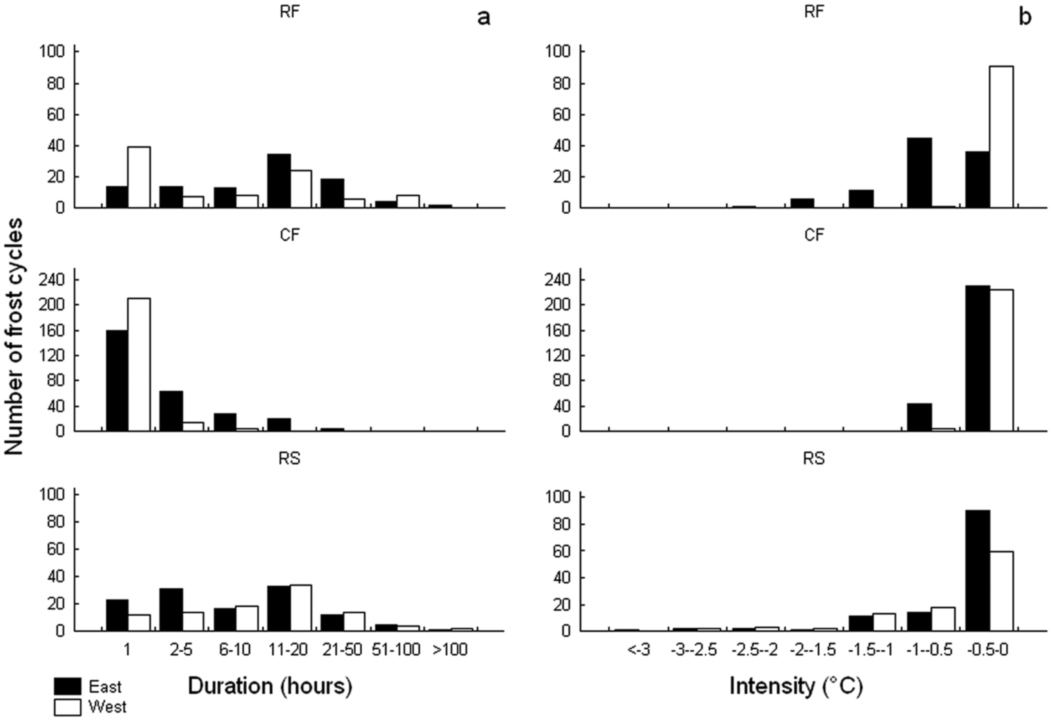

Fig. 3. Frequency distribution of (a) frost durations and (b) frost intensities at -2 cm for the three cushions. RF = round-flat, CF = crescent-flat, RS = round-slope. Notice the large number of short duration (especially evident at the CF cushion) frost cycles. Despite the substantial heave recorded frost cycle minima are predominantly above –2°C

but there were significant second order interactions. Depth and direction did not interact. However, there was a significant interaction between month and direction (F (5, 10) = 5.96, p <0.01). Mean temperatures on eastern cushion sides were lower in the colder months (June, July and August) than western cushion sides, whereas there were no differences between eastern and western cushion sides in the warmer months (Fig. 4a). This trend was strongest at 2 cm depth. Furthermore, a significant interaction between month and depth was found for mean temperature (F (10, 20) = 33.51, p <0.01). The 2 cm depth was lower than the other two depths in the colder months, with no differences in the warmer months.

For maximum temperatures, the third order interaction (month/depth/direction) was found to be significant (F (10, 20) = 3.59, p <0.01). For all three depths maximum temperatures on eastern cushion sides were lower than those on western cushion sides in winter months, but these directional differences were found to diminish in warmer months (Fig. 4b). Furthermore, the increase in maximum temperature towards summer declined with depth. Although maximum temperatures declined with depth during all months; this decline was stronger in warmer than in colder months.

No third order or second order interactions were found to be significant for minimum temperatures. No significant differences were found in minimum temperatures between eastern and western cushion sides. However, minimum temperatures increased significantly with depth (F (2, 4) = 12.84, p = 0.02) and July was found to have significantly higher minimum temperatures (F (5, 10) = 5.52, p = 0.01) than all the other months, except for October (results not shown).

Variability in temperature showed a significant third order (month/depth/direction) interaction (F (10, 20) = 4.34, p <0.01, Fig. 4c). Variability in temperature dropped with depth and evened out over the months with depth, so that at 10 cm, May and

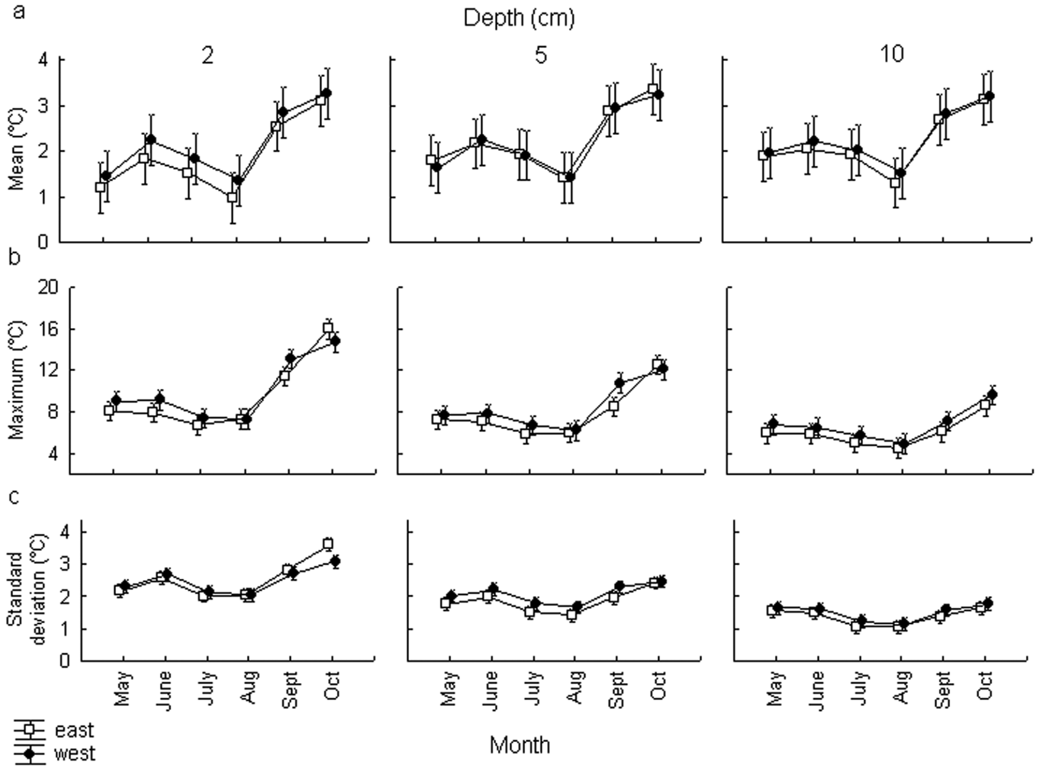

Fig. 4. Mean temperatures (a), maximum temperatures (b) and standard deviations of temperatures (c) were found to be slightly lower on eastern cushion sides than on western cushion sides in winter months. Results for minimum temperatures are not shown. Vertical bars denote 95% confidence levels

October had very similar variabilities, but at 2 cm variability in October was much higher than in May. Eastern cushion sides were less variable in colder months than western cushion sides, with the trend reversing in warmer months for the 2 cm depth (Fig. 4c). This was especially clear at the RS cushion (Fig. 2c). At the other two depths this trend had merely weakened (Fig. 4c).

Soil moisture data

Soil moisture differences between the eastern and western cushion side of the CF cushion were in the order of 2%. As the accuracy of the soil moisture probes is reported to typically be in the order of 4% (Decagon, Model EC-20, Decagon Devices, U.S.A.), these differences were not significant. However, soil moisture was above the values needed for needle ice growth, even for very coarse-grained soils and therefore posed no limit on needle ice growth potential (Meentemeyer and Zippin 1981).

Heave and erosion

Mean heave for all three cushions was between 80 and 90 mm, with a large number of dowels (between approximately 70 and 80% at each cushion) completely heaved out (Table 1).

No significant differences in heave were found between cushion sides (north/south and east/west, $p < 0.05$) for any of the three cushions. A weak, but significant positive correlation ($r = 0.20$, $p < 0.05$, $n = 198$) was found between heave and distance from cushion (Fig. 5a). However, dowels that were heaved out completely were found at any distance from the cushions.

For all three cushions, maximum erosion was close to or over 100 mm, with one value for the RF cushion as high as 160 mm (Table 1). This value was seen as an outlier and excluded from analyses, as it was far larger than the mean erosion value for any of the three cushions (Table 1).

No significant differences were found for ero-

Table 1. Mean, maximum and minimum heave and erosion for the three cushions. Maximum measurable heave was 100 mm. RF = round flat, CF = crescent flat, RS = round slope.

	Cushion	N	Mean ± s.d.	Max	Min	% Completely heaved
Heave (mm)	RF	44	82.0 ± 34.3	100.0	3.9	75.0
	CF	99	84.0 ± 34.3	100.0	–2.7	79.8
	RS	55	88.6 ± 19.6	100.0	25	69.1
Erosion (mm)	RF	58	16.2 ± 21.8	160.8	–27.7	
	CF	133	6.7 ± 15.2	98.8	–47.4	
	RS	65	7.6 ± 11.8	64.1	11.8	

sion between cushion sides (north/south and east/west). A weak, but significant positive correlation ($r = 0.14$, $p < 0.05$, $n = 256$) was found between erosion and distance from cushion (Fig. 5b).

Discussion

Soil thermal and moisture patterns do indeed show spatial variation as hypothesized. Our results indicate a thermally more uniform, but slightly cooler winter climate, on eastern cushion sides as opposed to western cushion sides. Fewer frost cycles were found on eastern cushion sides. The sustained period of temperatures at, but mostly just below 0°C at the surface layer on the eastern cushion side in Figure 2 (inlay) suggests snow accumulation on this cushion side to be present up to the warm front passage on 5 August. Snow accumulation on eastern cushion sides in winter explains the smaller variability in temperature, compared to western cushion sides. Larger temperature fluctuations on the western cushion side, compared to the eastern cushion side in Figure 2 (inlay) indicate that snow has not accumulated here, possibly as a result of high westerly wind speeds. As soil mean temperatures are positive, snow accumulation, and its subsequent melt, also has a cooling effect, which is consistent with lower mean values on the eastern side of cushions. In addition, the soil moisture data suggest that drying effects in the soil are more rapid and larger on western cushion sides (Fig. 2), whereas the eastern cushion side shows more stable soil moisture conditions, providing further support for our initial hypothesis that high wind conditions enhance evaporation on wind-exposed cushion sides.

Despite temperatures, numbers of frost cycles and soil moisture differing between eastern and western cushion sides, no directional differences in either frost heave or erosion were found between eastern and western cushion sides. Either these differences were too small to translate into aspect-differentiated heave, or there were actually differences in heave, but because the dowels were almost all heaved out, these differences could not be measured. Longer dowels or more frequent field measurements could be used to determine such differences.

Both heave and erosion values showed a slight tendency to increase with distance from the cushion edge. The micro-climatic data set provides no clue to this trend, but altered air flow patterns around the cushions may play a role. Furthermore, although some sediment removal against the cushion edges occurred, the erosion values right against the cushion edge were all under 2 cm and a number of values indicated burial of pins against the cushion edge. This accumulation of coarse material specifically on upslope cushion sides (Haussmann *et al.* 2009) will change the frost susceptibility of the material and may be another possible factor contributing towards the heave-distance trend. Lastly, soil strength provided by the cushion rooting structure, which is probably denser around the cushion edges, should also be considered.

The large number of heaved-out dowels clearly show that the study area was subjected to effective and extensive frost heave. Based on the shallow frost penetration of mostly less than 10 cm and numerous field observation reports (Hall 1979; Boelhouwers *et al.* 2003), needle ice growth is considered responsible for frost heave in the area. Despite such extensive frost heave, minimum temperatures hardly reached –2°C, the suggested required temperature for needle ice nucleation (Outcalt 1971). Our results strongly indicate that needle ice nucleation also occurs at temperatures above –2°C. Furthermore, our results suggest that frost heave took place by a frost pull mechanism and not frost push, as frost penetration in general did not reach 10 cm (the depth that most dowels were inserted). We view this frost pull of the dowels as a model for plant root damage, especially

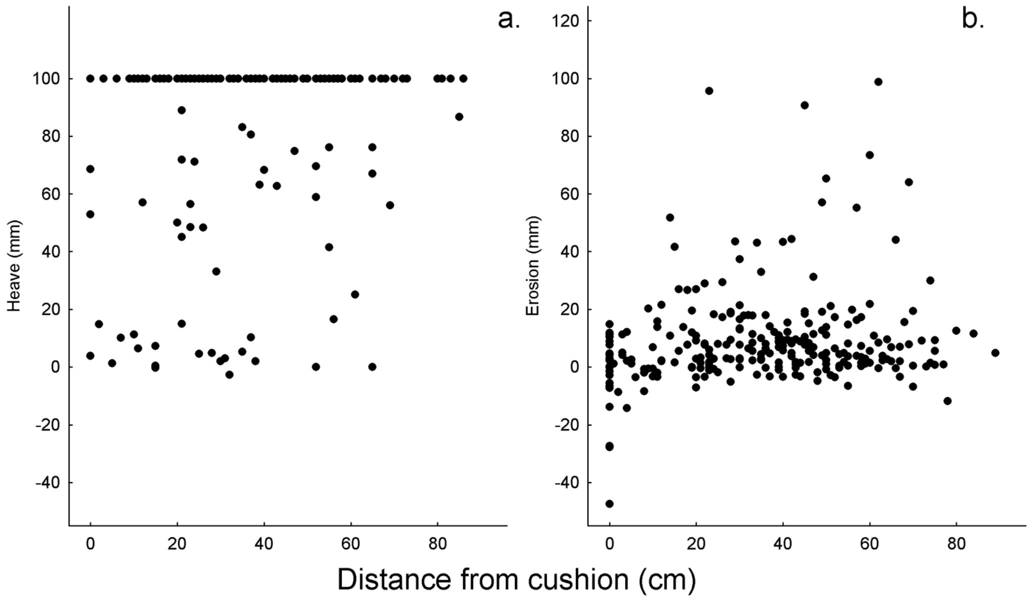

Fig. 5. Relationship between distance from cushion and (a) heave ($r = 0.20$, $p < 0.05$, $n = 198$) and (b) erosion ($r = 0.14$, $p < 0.05$, $n = 256$). Maximum measurable heave was 100 mm. Data for all three cushions are pooled

for very vulnerable individuals, such as seedlings with a single tap root. Our results therefore demonstrate the potential effect of needle ice growth on seedling mortality, as suggested by McGeoch *et al.* (2008).

The erosion data indicate the combined action of frost heave and surface runoff to be an important component of surface denudation. Ferrick and Gatto (2005) demonstrated that freeze-thaw cycles contribute towards soil erosion in cold climates and on Marion Island Boelhouwers *et al.* (2000) describe how frost heave by needle ice lifts cohesive soil and creates a friable surface layer of soil that is rapidly removed by surface flow. The unexpected high erosion values around the cushions suggest this mechanism may be more widespread on the more compact and shallow grey lava soils on the island and needs further investigation. Although care was taken to minimise initial site disturbance during sensor and marker installation this must also be considered a factor in the high erosion rates obtained. Newly exposed soil can be expected to be at erosion risk in response to the 860 mm of precipitation over the monitoring period.

Boelhouwers *et al.* (2003) ascribe *Azorella* cushion decay on Marion Island to turf exfoliation as a result of needle ice growth on leeward cushion sides. As a result, cushions at their study site were found to advance into the wind. In our study, however, the CF cushion was not found to advance into the wind, but rather in a northerly direction. Clearly cushion orientation is site specific and other factors, such as potentially solar radiation, also play a role. In addition, no directional differences in either frost heave or erosion were found around cushions. Again, as most dowels were completely heaved out it was difficult to determine whether there were not in actual fact directional differences in needle ice growth and frost heave rates.

Microarthropod communities have been shown to vary directionally inside *Azorella selago* cushions, with higher abundances on cooler, less windblown sides than on warmer, windy sides (Hugo *et al.* 2004). In addition, the grass, *Agrostis magellanica*, which grows epiphytically on *A. selago* cushions, has been found to be unequally distributed between plant sides (Le Roux *et al.* 2005). These studies illustrate the significance of microclimates created inside *Azorella* cushions (see also Nyakatya and McGeoch 2008). Our results emphasize that these subtle microclimatic differences exist not only inside *Azorella* cushions, but also in the surrounding soil, with potential consequences for biota. For example, it may be suggested that higher thermal variability in winter on wind-exposed, western cushion sides is likely to disfavour seedling establishment and microarthropod numbers, while snow accumulation sites on eastern cushion sides may provide more favourable micro-habitats. Clearly further work is needed to understand the complex micro-climate, soil frost process and vegetation interactions in this diurnal frost environment better.

The potential effects of climate change on freeze-thaw cycle characteristics are not yet fully understood (Henry 2008). Warming and drying trends, such as those experienced on the island (Le Roux and McGeoch 2008), have been predicted to increase cycle frequency as a result of decreased insulation by snow cover (Isard and Schaetzl 1998). This could therefore potentially have a larger impact on eastern cushion sides, where snow accumulates in winter. Furthermore, freeze-thaw cycles have been shown to affect soil properties ranging from physical soil properties to microbial biomass, microbial community composition and nutrient dynamics (see Henry 2007 for a recent review). Climate change could thus have potentially far-reaching consequences on the island's biota, not only through direct effects, but also indirectly through changing frost cycle dynamics and microclimate structure and functioning.

Conclusions

Winter soil temperatures were found to be lower and less variable and soil moisture more stable on eastern sides of *Azorella selago* cushions than on western cushion sides. This variability is probably the combined result of i) snow accumulation on leeward cushion sides, inducing insulation and cooling, and ii) drying on windward cushion sides. The very effective frost heave, often induced at temperatures above –2°C, predominantly resulted in complete dowel heave. As a result, no expected directional differences in frost heave could be demonstrated around cushions and therefore no evidence was found to suggest that frost heave is responsible for directional turf exfoliation and crescent cushion formation. Similarly, erosion rates showed no directionality around cushions. Further attention must be given to the consequences of the demonstrated microclimatic variations in assessing the role of *Azorella selago* as an ecosystem engineer in sub-Antarctic fellfield habitats. While more measurements on abiotic processes around cushions are clearly needed, directionality in microbiological activity and seedling establishment around cushions should also be included in future studies.

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